# Study on the Effective Thermal Conductivity of Fiber Reinforced Epoxy Composites

A THESIS SUBMITTED
IN PARTIAL FULFILLMENT OF THE REQUIREMENT FOR THE DEGREE OF

**Master of Technology**

In

**Mechanical Engineering**

(Specialization: Thermal Engineering)

By

**Yagya Kumar Sahu**
(Roll No. 212ME3320)

**Department of Mechanical Engineering**
**National Institute of Technology**
**Rourkela, Odisha (India)**

June, 2014

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By

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Under the supervision of

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**Rourkela, Odisha (India)**

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# C E RT I F I C A T E

This is to certify that the thesis entitled "***Study on the Effective Thermal Conductivity of Fiber Reinforced Epoxy Composites***", submitted by **Yagya Kumar Sahu** (Roll No: 212ME3320) has been carried out under my supervision in partial fulfilment of the requirements for the degree of ***Master of Technology*** in ***Mechanical Engineering (Specialization: Thermal Engineering)*** during session 2013 - 2014 in the Department of Mechanical Engineering, National Institute of Technology, Rourkela.

To the best of my knowledge, this work has not been submitted to any other University/Institute for the award of any degree or diploma.

Place: Rourkela

Date:

**Prof. Alok Satapathy**
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Odisha, India

# A C K N O W L E D G E M E N T

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# ABSTRACT

The present paper deals with the effect of volume fraction of fibers on the effective thermal conductivity ($k_{eff}$) for polymer composites. This work sees an opportunity of enhancement on insulation capability of a typical fiber reinforced polymer composite. A mathematical correlation for the effective thermal conductivity of polymer composites reinforced with fiber is developed using the law of minimal thermal resistance and equal law of the specific equivalent thermal conductivity. To validate this mathematical model, two sets of epoxy based composites, with fiber content ranging from 0 to 15.7 vol % have been prepared by simple hand lay-up technique. For one set of composite, natural fiber i.e. banana fibers are incorporated in epoxy matrix and for another set a well-known synthetic fiber i.e. glass fiber is taken as a filler material whereas matrix material remains the same. Thermal conductivities of these composite samples are measured as per ASTM standard E-1530 by using the Unitherm™ Model 2022 tester, which operates on the double guarded heat flow principle. Further, finite element method (FEM) is implemented to determine the $k_{eff}$ of such composites numerically using a commercially available finite element package ANSYS. Experimentally measured values are then compared with the values obtained from the proposed mathematical model, the numerical values and also with models established earlier, such as Rule-of-Mixture (ROM), Maxwell's model, Nielson-Lewis model and Bruggeman model. From the experimental and numerical output, it can be seen that with an increase in fiber content, there is gradual decrease in effective thermal conductivity value for both sets of composites. This comparison tells that while none of the established models are correctly predicting the effective thermal conductivity of the composites, the results obtained from the proposed model fits well with the experimental data. This study shows that the effective thermal conductivity reduces quite significantly as the fiber loading in the composite increases. A reduction of about 8 % in the value of thermal conductivity is recorded with addition of 15.7 vol % of glass fiber in epoxy resin whereas 12 % decrease is noticed when filler is banana fiber. This study validates the proposed model and also proves that finite element analysis can be an excellent methodology for such investigations. With light weight and reduced heat conductivity, these insulative, fibers reinforced polymer composites finds their potential applications in insulation boards, food containers, thermo flask, building materials etc.

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**Chapter – 1**

# INTRODUCTION

## 1.1 Background and Motivation

### ***Requirement of Thermal Insulation***

It is essential for comfort and in some cases, for the survival of humans and animals to retard the flow of heat by using some insulation medium. Insulation has many advantages in industry like it prohibits damage due to freezing of various articles or damage of articles by high temperatures, and lowers cost for heating and cooling. Heat flows from a hot body to a cold (i.e. less warm) body in one direction only so insulation helps to slow down this flow. In a refrigerator, for example, insulation retards the heat flow from the room air to the interior of the refrigerator. In a building, we can observe that insulation keeps out during summer heat and in during winter.

It can be observed that most of the studies in the field of thermal analysis of polymers are intended at enhancing the thermal conductivity of the polymer rather than trying to improve its insulation capabilities. In applications like pipe insulation, building insulation, thermo flasks and in food containers, thermal insulation is required. Also in space craft and automotive industries thermal insulation plays an important role.

Building materials that themselves are good insulators are used to insulate buildings. Building can be also insulated by providing spaces in walls and ceilings and by filling the spaces with an insulating material. Such simple building materials as the snow blocks of Eskimo igloos, the straw of thatched roofs, and the sun-baked clay houses in Northern Africa, the Middle East, and Latin America offer good insulation.

Materials considered exclusively as insulation commonly come as loose fills or in the form of batts backed with foil or paper. They are set up between the interior and exterior walls and in the floor or ceiling of the attic. Windows and doors are insulated by weather stripping around the frame and by creating a dead-air space through the use of storm windows and storm doors. Many parts of the country know-how large changes in temperature from season to season. So, there is a great necessity for building materials with insulating properties. With the development of new technologies, the scenario in industries of all kinds, transportation sector, and entertainment sector and even in the field of medical services is much the same. The conventional engineering materials are not capable to meet the requirement of these special properties like high strength, low density and low conductivity. The demand for structurally stable, cost effective and light-weight insulation materials is therefore increasing day by day. Foamed plastic is one of the generally used thermal insulation materials. However, its application is limited considerably due to its poor mechanical properties.

Synthetic fibers like glass fiber, nylon, carbon fiber etc. are considered to be potential filler material for various applications like wear resistant and structural components. Glass fiber reinforced polymer matrix composites are important engineering materials, mainly because of their low density in combination with excellent specific stiffness and strength. This synthetic fiber is found to be potential filler for improving insulation capability of various polymers because of its low thermal conductivity. But these synthetic fiber reinforced polymer composite have some disadvantages like they are corrosive and toxic in nature, higher cost and non-recyclable.

It is remarkable to note that natural fibers such as sisal, jute, coconut coir, rice husk, banana etc., are richly available but are not optimally utilized. At present, the use of these fibers are in the production of mats, ropes, yarns and matting as well as in production of fancy articles like table mats, handbags, wall hanging and purses. Cotton, banana and pineapple are also used in making cloth in addition to being used in the paper industry. With growing environmental responsiveness and ecological concern, attention towards natural fiber reinforced composites have increased during the recent decades. The composites have many advantages, including low cost, light weight, nontoxic, biodegradable etc. Various natural fillers like pineapple, sisal and bamboo, coconut coir, jute etc. as the reinforcements in composites have been reported earlier. Apart from this, natural fibers possess very low thermal conductivity which is much lower than synthetic fiber and can be used as filler for various insulation applications.

Therefore, there has been a focus to fabricate a kind of light, porous material with better mechanical strength and good thermal insulation properties. Against this backdrop, emerged a class of promising engineering insulation material– ***polymer composites***.

## 1.2 Composite Materials

There are basic two phase of composite material, in which one is known as matrix material and another one is called reinforcing material. The reinforcing material is embedded over matrix material. The matrix material is continuous phase and reinforcing is discontinuous phase. The reinforcing phase is much harder than matrix phase. In composite material matrix phase removes the stresses between reinforcing phase and also protect from mechanical and environmental damage. The function of reinforcing material is to improve mechanical and thermal properties of composites. Composite are hybrid of two or more material such as reinforced polymer, metal or ceramics. The reinforcement may be in the form of fibers, particles, whiskers or lamellae, and are incorporated in a suitable matrix, thereby providing a material that combines the most useful properties of the constituents. Generally the properties of composites are superior to those of its individual constituents. High structural strength, glass fiber reinforced plastics were developed in the early 1940's and the technology of reinforced polymers has progressed significantly since then. In a typical glass fiber reinforced plastic composite, the strength and stiffness are provided by the glass fiber while the temperature capabilities of the composites is governed by the plastic matric. These composites are finding increasing application in air craft, automobile industry.

**Matrix material**: - A variety of matrix polymer, metal, alloy, intermetallic, ceramics, carbon, cement etc. have been used for making composites. The matrix material serves several functions which are vital to the performance of the composite material. These functions also depend upon the type of reinforcement such as dispersions, particulates, whispers, discontinuous or continuous fibers. The matrix enables the composite to withstand compression, flexural and shear forces or tensile loads. The polymer material for a matrix can be thermosetting or thermoplastic resins. Thermoset resins, in the presence of a catalyst reaction or cure. Once cured these material can no longer flow. Thermosetting resins such as epoxies, bismaldeimides and cyanates can provide good strength properties. Thermoplastic resins are normally solids at room temperature but soften or melt when heated to elevated temperatures and become solid when cooled. Typical thermoplastic resins include polymide, polyami9de, polyphenylene sulphide (PPS), polyetherether ketone (PEEK), polyethylene terephthalate (PET), and polyetherulfone.

Thus speciality epoxy resins and curing agent designed for use in high performance composites have excellent elevated temperature resistance, good mechanical properties, low water absorption and relatively high glass transition temperature. Hence a proper combination of epoxy resin, modifying resin, reinforcing fiber, curing agent and processing procedure are required to take full advantages of their properties. Since the relatively low strength polymers can be converted into high strength composites by reinforcement, this field of the composite industry is well established and is growing faster into newer application.

**Reinforcement** - The reinforcement for composites may be in the form of particles, whiskers, fibers, lamellae or a mesh. They may increase the strength, stiffness or modify the failure mechanism advantageously. There can be special cases where the fibers may conduct or resist heat and electricity. Whiskers of metals, inter-metallic, oxides, carbides and nitrides are frequently used as reinforcement. A variety of continuous fibers of glass, carbon Kevlar (aramid), silicon carbide, alumina, boron, tungsten etc. are used as reinforcement.

## 1.3 Types of Composite Materials

On the basis of matrix material composite materials can be classified into three groups. They are:

1.3.1 Metal Matrix Composites (MMC)
1.3.2 Ceramic Matrix Composites (CMC)
1.3.3 Polymer Matrix Composites (PMC)

### 1.3.1 Metal matrix composites:

Metal matrix composite made a breakthrough in the development of useful properties of metals and alloys in relation to the traditional approach of alloying and heat treatment. These composites, containing discontinuous or continuous reinforcement with particulates, whiskers or fibers are capable of providing properties not achievable in monolithic alloys. Ceramic particles or whiskers dispersed in a metal matrix either by powder metallurgy or molten metal processing can enhance the modulus, strength, wear resistance, elevated temperature properties or control of thermal conductivity or coefficient of thermal expansion.

The improved thermal conductivity and controlled coefficient of thermal expansion of SiC particle reinforced aluminum matrix composites are finding newer application as electronics packaging matrerials. Many potential aerospace applications have been identified for MMC. These are also having automotive applications.

### 1.3.2 Ceramic matrix composites:

Ceramics are characterized by lightness, hardness, corrosion and oxidation resistance and superior elevated temperature properties. Hence many ceramic matrix composites can be used as temperatures higher than those of the polymer and metal matrix composites. Important ceramic matrixes are oxides, carbides, nitrides, borides, glasses, glass-ceramics and silicates. The reinforcements used are SiC, Si3N4, Al2O3, BN, ZrO2, AIN and C in the form of fibers, whiskers or particulates. These composites are processed by sintering, hot pressing, hot isotactic pressing, infiltration, reaction bonding and combustion synthesis. Currently ceramic matrix composites are used as cutting tool inserts wear resistant composites, space shuttle tiles and aerospace components. Other potential application includes engine components, armor of military vehicles, and leading edge application in aerospace and high temperature corrosion resistant parts. Other potential application includes bio-ceramic and high temperature ceramic super conductor composite wires for power transmission cables, motors and super conducting magnetic energy storage system.

### 1.3.3 Polymer matrix composites:

In case of the reinforced plastics, the characteristics of the desired end product such as size, shape, function and quality determine the method by which the basic materials are combined, moulded, cured and machined. Prominent moulding process for reinforced plastics includes hand lay-up, spray up moulding, prepreg lay-up (vacuum bag and auto-clave moulding), press moulding (SMC, BMC etc.), resin injection moulding and filament winding. To make useful structure, the composite materials have to be joined and machined,

The industrial applications of reinforced plastics have spread a wide spectrum of consumer goods, constructions, chemical plants, marine and road transportation and aerospace components. Mechanical engineering products include cylinders, rolls, shafts, coupling, spindles, robot arms, covering etc. the aerospace industry used a wide range of products including floor panels, skin panels, elevators, wings, flaps, covers, tanks, struts and rotor blades.

## 1.4 Types of polymer composites

Broadly, polymer composites can be classified into three groups on the basis of reinforcing material. They are:

- Fiber reinforced polymer ( FRP )
- Particle  reinforced polymer ( PRP )

### 1.4.1 Fiber reinforced polymer

It is also known as fibre-reinforced plastic. In this type of polymer composite fibres are reinforced with a polymer matrix. The common used fibres are glass, carbon, or aramid, while other fibres such as paper or wood or asbestos can also be used. The Fibre reinforced polymer composites can potentially application in the aerospace, automotive, marine, and construction industries.

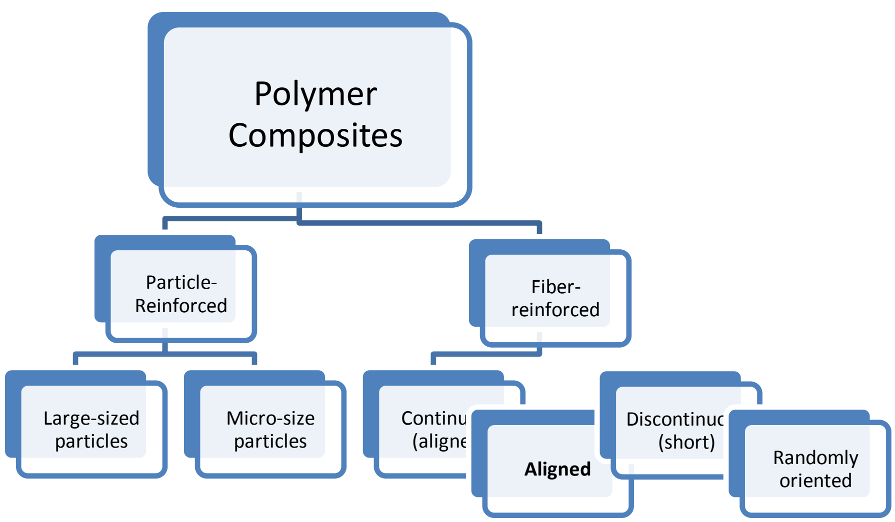


**Fig. 1.1** Classification of composites based on reinforcement type

### 1.4.2 Particle reinforced polymer

Particulate composites have an additive constituent which is essentially one or two dimensionally and macroscopic /microscopic. In some composites however, the additive constituent is macroscopically non-dimensionally, i.e., conceptually a point, as opposed to a line or an area.

Only on the microscopic scales does it become dimensional, i.e., a particle, and thus the concept of composite must come down to the microscopic level if it is to encompass all the composite of interest of engineers. Particulate composites differ from the fiber flake types in that distribution of the additive constituent is usually random rather than controlled. Particulate composite are therefore usually isotropic. This family of composites includes dispersion-hardened alloy and cermet.

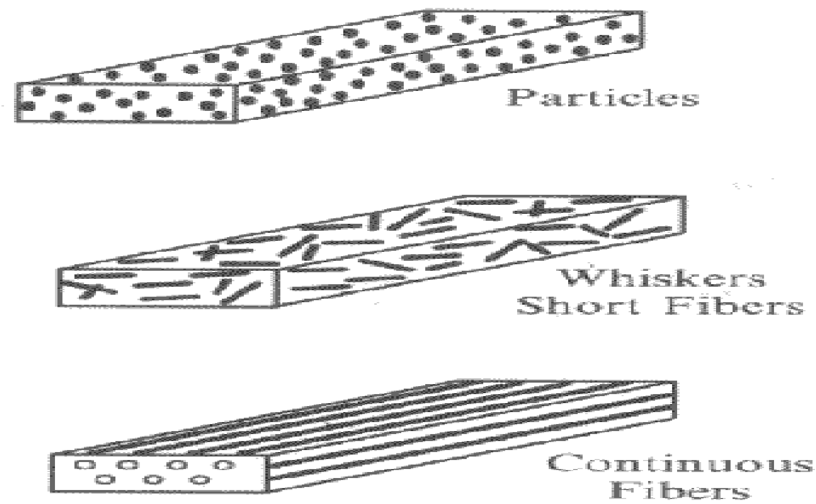


**Fig. 1.2** Different types of composites

## 1.5 Introduction to research work

The main function of insulation is to retard the heat flow and maintain temperature. It serves as thermal resistance and therefore prevents the damage of various devices and other articles which need to be maintained at constant temperature range. A thermal insulation performance of composite is influenced by three factors, i.e. solid conduction, gas conduction, and radiation heat transfer. Cellulose based insulation materials are dry plant materials like rice husk, and other agriculture wastes. Other available insulating materials are mineral wool, fiberglass, asbestos, wood, concrete, vegetable fiber, vermiculite and foamed plastics such as polystyrene, some of which depend on air pockets for much of their insulating effect. These substances retard the conduction and convection of heat transfer. The demand for low cost, structurally stable, effective and light-weight insulation materials is therefore increasing day by day. Synthetic and natural both the fibers have good insulation properties. So these fibers have a lot of research in this field.

In view of this, the present work has been undertaken to investigate the effect of adding insulative short fibers on the thermal conductivity of polymer resin. The main objective of the present work includes fabrication of a new class of low cost composites in which short banana fibers and short glass fibers are used as reinforcement to enhance the insulating capabilities of epoxy resin. A mathematical model is developed to evaluate $k_{eff}$ using the law of minimal thermal resistance and equal law of the specific equivalent thermal conductivity. Based on this model, a correlation between the effective thermal conductivity of the composite and the fiber content is proposed. Short glass fiber and short banana fiber are the two fillers used in present investigation reinforced individually in epoxy resin to fabricate two sets of composites by hand lay-up technique. The proposed model is then validated through experimentation conducted in controlled laboratory conditions. The $k_{eff}$ of all the fabricated composites with different compositions are numerically evaluated using finite element method and the results are validated through measured values. The comparison of $k_{eff}$ values obtained from incorporation of two different fibers is also reported in present work.

## 1.6 Thesis outline

The remainder of this thesis is organized as follows:

Chapter 2: Includes a literature review designed to provide a summary of the base of knowledge already available involving the issues of interest. It presents the research works of previous investigators on fiber reinforced polymer composites with emphasis on their structural properties and thermal conductivity.

Chapter 3: Includes a description of the raw materials and the test procedures. It presents the details of fabrication and characterization of the composites under investigation. It also describes the steps of FEM analysis.

Chapter 4: Presents the results of numerical, mathematical model and experimental investigation on the thermal conductivity of the composites under study.

Chapter 5: Provides a summary of the findings of this research work outlines specific conclusions drawn from both the experimental and analytical efforts and suggests ideas and directions for future research.

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Chapter - 2

# LITERATURE REVIEW

This chapter includes a survey of the past research already available involving the issues of interest. It presents the research works on the fiber reinforced polymer composites and the influence of various factors on the performance of composites studied by various investigators. The literature review is done based in the following points:

## 2.1 Study on synthetic fiber based polymer composites

A great deal of work has been done by many researchers on synthetic fiber reinforced polymer composites. Marom et al. [1] concentrated on the elastic properties of synthetic fiber-reinforced polymer composite materials that pertain to biomedical applications and demonstrates the range of stiffness obtainable through selection of constituents and by choice of angle of reinforcement. Vijay et al. [2] delivered an in depth analysis and comprehensive knowledge to the beginners in the field of natural cellulose fibers/polymer composites. The main aim of this review article is to reveal the current development and emerging applications of natural cellulose fibers and their polymer materials. Yongli [3] studied the mechanical behaviours of unidirectional flax and glass fiber reinforced hybrid composites with the aim of investigation on the hybrid effects of the composites made by natural and synthetic fibers. Cho et al. [4] investigated the mechanical behaviour of carbon fiber/epoxy composites and obtained that the composites reinforced with nanoparticles improved mechanical properties such as enhanced compressive strength and enplane shear properties. Chauhan et al. [5] studied on the influence of fiber loading on mechanical properties, friction and wear behaviour of vinyl ester composites under dry and water lubricated conditions and reported that the density of composite specimens is affected marginally by increasing the fiber content. Huang et al. [6] studied on effect of water absorption on the mechanical properties of glass/polyester composites. It was established that the breaking strength and tensile stress of the composites decreased gradually with increased water immersion time because the weakening of bonding between fiber and matrix.

## 2.2 Structure and property of glass fiber

Glass fiber is one of the most widely used filler which are being incorporated in polymers. Glass fiber is a lightweight, extremely strong and robust material. Stephen and Thomas [7] studied that the bulk strength and weight properties of glass fiber are favorable properties when compared to metals, and also it is easily moldable. Jiang and Zhang [8] studied that the glass is considered a vitreous super cooled liquid that is in a thermodynamically metastable state between the molten liquid state and the crystalline state. Different glass structures are influenced by the thermal history of the cooling process. Some typical properties of two important classes of glass fibers are shown in Table 2.1.

**Table 2.1 Typical properties of glass fibers**

| Material | Density (g/cm3) | Tensile strength (MPa) | Young's Modulus (GPa) | CTE (10-6K) |
|---|---|---|---|---|
| S-Glass | 2.55 | 3400 | 73 | 5.0 |
| E-Glass | 2.49 | 4400 | 86 | 5.6 |

## 2.3 Study on glass fiber reinforced polymer composites

A great deal of work has been reported by many researchers on glass fiber based polymer composites. Alexander et al. [9] investigated the influence of filler structure on electrical and mechanical properties of unidirectional glass-fiber-reinforced polyethylene (GF/PE). Both, carbon black and recycled short carbon fibers were used. A good correlation was found between mechanical properties and the specific electrical conductivity of the thermoplastic composites. Olmos and Benito [10] studied the effect that the use of glass fibers has on the morphology developed by a thermoplastic polymer modified epoxy. In particular, three surface modifications of the glass fibers were studied. These results might be attributed to a gradual phase separation process due to stoichiometric gradients which, on the other hand, seems to be conditioned by the nature of glass fibers surface. Bergeret et al. [11] studied the properties of short glass fiber reinforced thermoplastic composites based on poly (ethylene terephthalate), poly (butylene terephthalate) and polyamide-6, 6 in an aggressive environment is reported. Barre et al. [12] determined the tensile dynamic behavior of glass fiber-reinforced phenolic and polyester resins in order to find the influence of strain rate on the mechanical properties of composite materials produced by the resin transfer moulding (RTM) and pultrusion processes. The influence of the reinforcement structure is emphasized and shown to be effective. Rosa et al. [13] studied the application of life cycle assessment (LCA) methodology in order to explore the possibility of improving the eco efficiency of glass fiber composite materials by replacing part of the glass fibers with hemp mats. The main purpose and contribution of this study is the exploration of the eco-efficiency of this new material. The study is a development of a previous work conducted on a pipe system used to transport cooling sea waters in a Sicilian petrochemical company. Husic et al. [14] prepared two series of polyurethane resins using Soypolyol 204 derived from soyabean oil and petrochemical polyol Jeffol G30-650. Polyurethanes from soybean oil have good thermal, oxidative and weather stability, and can be used as a matrix in composite materials. The objective of this study was to compare the mechanical properties of untreated E-glass fiber reinforced composites prepared with soybean oil-based polyurethanes to that of the petrochemical polyol based ones.

## 2.4 Study on the natural fiber based polymer composites

In recent years, the interest of scientists and engineers has turned over on utilizing plant fibers as effectively and economically as possible to produce good quality fiber-reinforced polymer composites for structural, building, and other needs. It is because of the high availability and has led to the development of alternative materials instead of conventional or man-made ones. Many types of natural fibers have been investigated for their use in polymer such as wood fiber [15], sisal [16], pineapple [17], jute [18] and banana [19].

Bax and Mussing [20] investigated the mechanical properties of PLA reinforced with cordenka rayon fibers, respectively. A poor adhesion was observed using Scanning Electron Microscopy analysis. The highest impact strength and tensile strength were found for cordenka reinforced PLA at fiber proportion of 30 %. Waikamboo and Ansell [21] evaluated the physical and mechanical properties of the natural fiber composites to assess their serviceability. Treated fibers with highest strength were used as reinforcement for cashew nut shell liquid matrix and determined tensile properties, porosity and also examined fracture surface topography of the composites. The objective was to maximize the amount of low cost natural resources in the composite. They concluded that the presence of lignin in the untreated hemp fiber offers additional cross linking sites and the untreated fiber surface is more compatible with CNSL (Cashew Nut Shell Liquid resin) than alkali surface.

## 2.5 Structure and property of banana fiber

It is remarkable to note that natural fibers such as jute, coir, banana, sisal, etc., are richly available in developing countries like India, Srilanka and some of the African countries, but are not optimally utilized. At present, these fibers are used for the production of yarns, ropes, mats and matting as well as in making fancy articles like wall hanging, table mats, handbags and purses. Fibers such as cotton, banana and pineapple are also used in making cloth in addition to being used in the paper industry. It is a well-known fact that banana is one of the oldest cultivated plants in the world. The nutritional facts of the banana are (100g pulp); Carbohydrates 18.8 g; protein 1.15g; fat 0.18g; water 73.9g; vitamins C1 B1 B2 B6 E; other minerals 0.83 g and 81 kcal [22]. Banana-trees produce generally 30 large leaves (almost 2m long and 30-60cm wide) [23]. The micrographs of the longitudinal section and cross section of the banana fiber strands were taken. The cross sectional area of the banana fiber was investigated by using Optical laser beam equipment by Murali et al [24], and it was found to be 0.3596mm2. The plot of stress vs. percentage of strain for banana fiber is approximately linear; witj a stress value of around 560 MPa, when the % of the strain is 3.5.

A truck model ‘Manaca’ was developed and tested by Al-Qureshi [25], using banana fiber and epoxy resin. However, some special and critical panels were made of hybrid composites of glass/banana fibers. The vehicle went through many years of road performance tests and provided excellent results.

## 2.6 Banana fiber reinforced thermo plastic composites

Banana fiber was used as reinforcement with various thermoplastics, namely, Polypropylene (PP), Low Density Polyethylene (LDPE), High Density Polyethylene (HDPE), Polystyrene (PS) and Poly Vinyl Chloride (PVC). A comparative analysis of the experimental tensile properties with various theories of reinforced was also made. It shows that the Modified Rule of mixture has better correlation with the experimental values. The influence of Sisal, banana, jute and flax fiber morphology on the mechanical properties was studied by Kristina et al [26]. The composites are produced by extrusion method. Of the various fibers compared, sisal fiber has better impact properties, because it has better elongation to break. The result shows that the micro fibrillar angle also has a significant effect on the properties of the fiber. The performance evaluation of the hybrid composite of banana/glass fiber with PP was carried out by Sushanta et al [27]. The study shows that the addition of fibers in the PP matrix increases the mechanical properties up to 30wt % of the banana and glass as reinforcement in equal proportion. The dynamic mechanical analysis shows that at all temperature ranges of 20-1000C; the storage modulus of the composite is superior to the matrix. The bio-degradability of banana, pineapple and bamboo fibers reinforce with PP matrix was studied by Sanjay et al [28]. The investigation shows that the composite exhibits only 5-15 % of degradation.

A comparative study of fibers from cotton, rice straw, and bagasse and banana plant as reinforcement in LDPE was conducted by Youssef et al [29]. The study revealed that better tensile and thermal properties are achieved when maleated low density polyethylene is used as a matrix, when compared to untreated LDPE. Further, it also shows that the chemical composition of the natural fibers has a sting influence on the mechanical properties of the composite.

The influence of the fiber content, fiber loading, and hybrid effect on the mechanical properties of banana/glass hybrid composite was studied by Anshida et al [30]. The modification of the banana fiber by alkali, benzoylation and PSMA treatments improved the interface adhesion, and hence, the mechanical properties of the composite. The experimental and theoretical comparison of the tensile properties shows close agreement, except for the parallel model of reinforcement. The disagreement with the parallel model is due to formation of micro-voids and agglomeration of irregular shaped cellulose in the matrix, which decreases the stress transfer rate.

## 2.7 Banana fiber reinforced thermoset composites

Composite of various thermoset matrices (Polyester, Phenol formaldehyde, Urea Formaldehyde and epoxy) reinforced with banana fibers were investigated by various researchers. Banana fiber reinforced with polyester matrix was extensively investigated by Laly et al [31]. The studied shows that the effect of the fiber length and content on mechanical properties of the composite. The investigation shows that the fiber length of 30-40 mm and 40 % volume content has better mechanical properties. Further, aging decreases the mechanical properties of the composite because of the affinity of the banana fibers towards moisture. The mechanical and water absorption behavior of banana fiber composite prepared by resin transfer moulding method shows that the maximum tensile, flexural and impact strength is achieved at 30 mm fiber length and 40vol%. It also showed that the maximum diffusion, sorption, and permeability coefficient are achieved at 50vol% [32]. The twisted form of banana yarn was placed on the warp direction and alternate bundles of banana and yarns are weaved in weft direction. It indicates that the tensile strength was the maximum for the two layered composite, whereas flexural strength is the maximum for the tri-layer and the impact strength increases with the number of layers. The storage modulus is maximum for the four layers woven composite, and further addition of layers shows the addition of peaks for the loss modulus of the hybrid woven composite. The effect of chemical treatment on the flexural, impact and water absorption properties of woven banana-polyester composite was analyzed by Jannah et al. [33]. The result indicates that up to 10vol % and 15vol% the flexural and impact strength of the treated composite increased. Further, the addition of fibers results in degrading the propertied due to poor adhesion. The chemical modification of banana fiber using silane as the coupling agent has showed that the dielectric constant values decreases due to the change in hydrophilic nature of the fiber surface. It also show that's that the dielectric constant measurement will serve as a tool for predicting the fiber-matrix adhesion [34]. The effect of the layering arrangement on the storage modulus, loss modulus and damping property of banana/sisal hybrid composite was studied by Mariers et al. [35] as the function of temperature and frequency. It shows that the trilayer composite of banana fiber as skin and sisal as the core layer has maximum stiffness property.

The comparative study of Phenol Formaldehyde (PF) reinforced with banana and glass fibers showed that optimum mechanical properties are achieved at different fiber lengths. The interface adhesion was better between banana fiber and phenol formaldehyde when compared with glass fiber and phenol formaldehyde, which was determined from the single fiber pull-out test. It also revealed that the specific properties of the banana fiber- PF are superior to those of the glass fiber- PF composite [36].

## 2.8 Study on thermal conductivity of fiber reinforced polymer composites

A great deal of research work has been reported by various authors on the study of fiber reinforced composites. Dong-Pyo Kim et al [37] studied the glass fiber reinforced polymetalphosphate matrix composites prepared by a simple process displayed excellent thermal insulating and mechanical properties. Schuster et al [38] investigated the effect of three-dimensional fiber reinforcement on the out-of-plane thermal conductivity of composite materials. Using finite element models to better understand the behavior of the composite material, improvements to an existing analytical model were performed to predict the effective thermal conductivity as a function of the composite material properties and in-contact thermal material properties. Zhidong et al [39] studied the dependence of thermal conductivity of nanotubes on the atomic structure, the tube size, the morphology, the defect. The roles of particle/polymer and particle/particle interfaces on the thermal conductivity of polymer/CNT nano composites are discussed in detail. Yüksel et el [40] studied the temperature dependence of effective thermal conductivity (ETC) for samples of binary, ternary, and quadruple glass wools reinforced with aluminum foil was examined. The experiments were realized by the guarded hot plate in temperature differences of 5, 10 and 15 °C and the temperatures of 25 and 40 °C. The results revealed that in the case of reinforcing the aluminium foil, ETC increased with increasing the temperature or changing of temperature difference (5, and 15 °C). Hang et al [41] investigated thermal transport mechanisms and characterized when highly conductive fibers are embedded across the thickness of a three-dimensional polymer composite. An experimental setup was designed, fabricated and validated to measure through-thickness thermal conductivity.

## 2.9 Study on effective thermal conductivity analytical models

Numerous theoretical and empirical models have been proposed in the past to estimate and predict the effective thermal conductivities of fiber reinforced polymer composites. Comprehensive review articles have discussed the pertinent applicability of many of these analytical models. The simplest alternative for a two-component composite system would be with the arrangement of materials in either parallel or series with respect to heat flow which gives the upper or lower bounds of effective thermal conductivity.

For parallel conduction model [42, 43]

$$k_c = \left(1-\phi_1-\phi_2\right)k_m + \phi_1 k_{f_1} + \phi_2 k_{f_2} \tag{2.1}$$

where, $k_{f1}$, $k_{f2}$, $k_m$, $k_c$ are thermal conductivities of 1st filler, 2nd filler, composite matrix, conductivity of the composite as a whole and $\phi 1$ and $\phi 2$ are volume fractions of 1st and 2nd filler respectively.

For series conduction model [42, 43]

$$\frac{1}{k_c} = \frac{1-\phi_1-\phi_2}{k_m} + \frac{1}{k_{f_1}} + \frac{1}{k_{f_2}} \tag{2.2}$$

The correlations represented by Equations (3.1) and (3.2) are derived on the basis of the rules-of-mixture.

The geometric mean model [42, 43], also known as Ratcliffe Empirical Model gives the effective thermal conductivity as:

$$k_c = k_m^{(1-\phi_1-\phi_2)} k_{f_1}^{\phi_1} k_{f_2}^{\phi_2} \tag{2.3}$$

Bruggeman [44] derived an equation employing different assumptions for permeability and field strength for dilute suspension of spheres for a homogeneous medium and the implicit equation is given as:

$$1-\phi = \left[\frac{k_c - k_f}{k_m - k_f}\right]\left(\frac{k_m}{k_c}\right)^{1/3} \tag{2.4}$$

Maxwell [45] has obtained an exact expression for thermal conductivity, using potential theory for an infinitely dilute composite of spherical particulates dispersed randomly and devoid of mutual interaction in a homogeneous medium, which is given by

$$k_c = k_m \left[ \frac{k_f + 2k_m + 2\phi\left(k_f - k_m\right)}{k_f + 2k_m - 2\phi\left(k_f - k_m\right)} \right] \qquad (2.5)$$

Where, $k_c$, $k_m$ and $k_f$ are thermal conductivities of composite, continuous- phase (matrix), and dispersed-phase (filler) respectively, and ϕ is the volume fraction of the dispersed-phase.

Lord Reyleigh [45] extended Maxwell's solution by considering the thermal interaction between particles. For a cubic array the following expression was derived for the thermal conductivity:

$$k_e = k_m \left[ \frac{2k_m + k_f - 2\phi - 0.525\left(\frac{3k_m - 3k_f}{4k_m + 3k_f}\right)\phi_f^{10/3}}{\frac{2k_m + k_f}{k_m - k_f} + \phi - 0.525\left(\frac{3k_m - 3k_f}{4k_m + 4k_f}\right)\phi_f^{10/3}} \right] \qquad (2.6)$$

Here, $k_e$ is the effective thermal conductivity of the composite. This reduces to Maxwell's equation whenever 'ϕ' is sufficiently small and the last term may be neglected.

Lewis and Nielsen [42] derived a semi-theoretical model by modification of the Halpin-Tsai equation for a two phase system which assumes an isotropic particulate reinforcement and also takes into consideration the shape of particle as well as its orientation.

$$k_c = k_m \left[ \frac{1 + AB\phi}{1 - B\phi\psi} \right] \qquad (2.7)$$

$$B = \left[ \frac{\left(k_f / k_m\right) - 1}{\left(k_f / k_m\right) + A} \right] and, \psi = 1 + \left[ \frac{1 - \phi_m}{\phi_m^2} \right]$$

Where, $k_f$ is thermal conductivity of filler material and 'ϕ' is the volume fraction of filler material.

## 2.10 The knowledge gap

In the past, a number of studies have been published on the thermal conductivity of particulate composites but a very few investigation has been carried out on the thermal conductivity of fiber reinforced polymer composites so that there is a huge knowledge gap that demands a well-planned and systematic research in this area of fiber reinforced polymer composites. A comprehensive evaluation of the available literature tells that:

- Most of the studies are intended at improving the heat conduction capacity of the polymer rather than trying to improve its insulation capability.

- Even though a large number of particulates and fibers have been used as fillers in the past, there is no report available on natural fibers like banana fiber being used for composite making for the insulation purpose.

- Investigation on heat conduction mechanism of fiber reinforced polymer composites is rare.

- The understanding of the relationship between the effective thermal conductivity of a composite material and the micro-structural properties (volume fractions, distribution of fibers, size of fibers, properties of individual components, etc.) is far from satisfactory.

Further, though it becomes clear that improvisation on thermal conductivity of polymers may be achieved either by molecular orientation or by the addition of conductive fillers, it is yet to be seen how the incorporation of natural fibers with poor heat conductivity affects the overall conductivity of any polymer composite.

## 2.11 Objective of the present investigation

The objectives of this work are outlined as follows:

1. To evaluate effective thermal conductivity of fiber reinforced polymer composites, a mathematical model is developed.

2. To validate this mathematical model, two sets of epoxy based composites have been fabricated.

3. For one set of composite, a well-known synthetic fiber i.e. glass fibers are incorporated in epoxy matrix and for another set low cost natural fiber i.e. banana fiber is taken as a filler material whereas matrix material remains the same.

4. Objective of the study is improving the thermal insulation properties of fiber reinforced polyester composite with decreasing the effective thermal conductivity of composite system.

5. Measurement of effective thermal conductivity ($K_{eff}$) of the fabricated fiber reinforced polymer composite (with different volume fraction) experimentally.

6. Estimation of effective thermal conductivity of these fiber reinforced polymer composite systems using Finite Element Method (FEM).Three dimensional cylinders in cube models are constructed to simulate the microstructure of the composite materials for various filler concentrations.

7. Validation of the proposed model by comparing the thermal conductivity values obtained from the proposed model with the values obtained from the FEM analysis and experimentation.

8. Finally, recommending the above fabricated composites for specific applications**.**

## Chapter Summary

This chapter has provided an exhaustive review of research works on fiber reinforced polymer composites, thermal conductivity of polymer matrix composites and on thermal conductivity models reported by various investigators. It has also clearly outlined the objectives of the present work.

The next chapter discusses the mathematical model development to evaluate effective thermal conductivity of fiber reinforced polymer composites.

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Chapter – 3

# MATERIALS AND METHODS

The volume fraction and the fiber distribution are found to be more critical than polymer selection for enhancement thermal insulation. This chapter describes the materials and methods used for the processing of the composites under this investigation. It presents the details of the characterization and thermal conductivity tests which the composite samples are subjected. The numerical methodology related to the determination of thermal conductivity based on finite element method is also presented in this chapter.

## 3.1 Materials

### 3.1.1 Matrix material

Matrix materials are of different types like metals, ceramics and polymers. Polymer matrices are most commonly used because of cost efficiency, ease of fabricating complex parts with less tooling cost and they also have excellent room temperature properties when compared to metals and ceramic matrices. Polymer matrices can be either thermoplastic or thermoset. Thermoset matrices are formed due to an irreversible chemical transformation of the resin into an amorphous cross-linked polymer matrix. Due to huge molecular structures, thermoset resins provide good electrical and thermal insulation. They have low viscosity, which allow proper fiber wet out, excellent thermal stability and better creep resistance.

The most commonly used thermoset resins are epoxy, polyester, vinyl ester and phenolics. Among them, the epoxy resins are being widely used for many advanced composites due to their excellent adhesion to a wide variety of fibers, superior mechanical and electrical properties and good performance at elevated temperatures. In addition to that they have low shrinkage upon curing and good chemical resistance. Due to several advantages over other thermoset polymers, epoxy (LY 556) is chosen as the matrix material for the present research work. It chemically belongs to the ‘epoxide’ family. Its common name is Bisphenol-A-Diglycidyl-Ether (commonly abbreviated to DGEBA or BADGE) and its molecular chain structure is shown in Figure 3.1. It provides a solvent free room temperature curing system when it is combined with the hardener tri-ethylene-tetramine (TETA) which is an aliphatic primary amine with commercial designation

HY 951 (Figure 3.2). The LY 556 epoxy resin (Figure 3.3) and the corresponding hardener HY-951 are procured from Ciba Geigy India Ltd. Table 3.1 provides some of the important properties of epoxy.

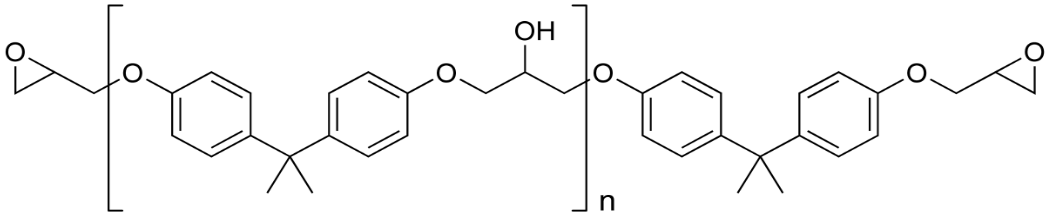


**Fig. 3.1** Unmodified epoxy resin chain ('n' denotes number of polymerized unit)

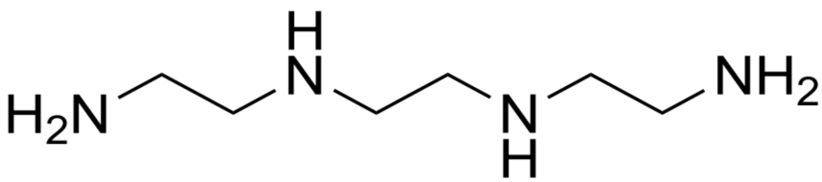


**Fig. 3.2** Tri-ethylene-tetramine (hardener used for epoxy matrix)

**Table 3.1** Some important properties of epoxy

| Characteristic Property | Inferences |
|---|---|
| Density | 1.1 gm/cc |
| Compressive strength | 90 MPa |
| Tensile strength | 58 MPa |
| Thermal conductivity | 0.363 W/m-K |
| Glass transition temperature | 104°C |
| Coefficient of Thermal expansion | 62.83 ppm /°C |
| Electrical conductivity | $0.105 \times 10^{-16}$ S/cm |


**Fig. 3.3** Epoxy resin and hardener

### 3.1.2 Filler material - 1 :( Glass fiber)

For fabrication of polymer composite a well-known synthetic fiber i.e. short glass fiber is used as filler material. It is the one of the most widely used reinforcements. Glass fiber is formed when thin strands of silica based or other formulation glass are extruded into many fibers with small diameters suitable for textile processing. The first commercial production of glass fiber was in 1936. Glass fiber is considered as a filler material because of its low density (1.5 gm/cm3); also it happens to be extremely strong and robust material. Most importantly it is insulating in nature (0.18 W/m-K). Uses for regular glass fiber include mats and fabric for thermal insulation, electrical insulation, sound insulation, high strength fabric, heat and corrosion resistant fabric. Glass fiber is extensively used for making FRP tanks and vessels. Glass fibers used in present investigation are procured from Saint Govion, India. Table 3.2 provides some of the important properties of glass fiber. Figure 3.4 shows short glass fiber used as filler in the present investigation.

**Table 3.2** Some important properties of glass fiber

| Characteristic Property | Inferences |
|---|---|
| Density | 1.5 gm/cc |
| Compressive strength | 1080 MPa |
| Tensile strength | 3445 MPa |
| Thermal conductivity | 0.18 W/m-K |

**Fig. 3.4** Short glass fiber used as filler in the present work

### 3.1.3 Filler material - 2 :( Banana fiber)

For fabrication of second set of polymer composite natural fiber i.e. banana fiber is used as filler material. Scientific name of banana is musa acuminata. They have a high tensile strength and resist rot. Historically they have been used to make rope. Main organic constituents of banana fiber are: cellulose, hemicellulose, pectin, lignin and some extractives. Banana fiber is considered to be remarkable filler because of its very low density (0.2 gm/cm$^3$), low cost, nontoxic, biodegradable and environmental friendly nature. It possesses very low thermal conductivity (0.09 W/m-K) which is prime requirement for present investigation. Banana fibers are used for making cloths, paper, ropes etc. Banana fibers used in present investigation are procured from M/s ROPE (Rural Opportunity Production Enterprises) International, India. Table 3.2 provides some of the important properties of banana fiber. Figure 3.5 shows short banana fiber used as filler in the present work.

**Table 3.3** Some important properties of banana fiber

| Characteristic Property | Inferences |
|---|---|
| Density | 0.2 gm/cc |
| Compressive strength | 22.25 MPa |
| Tensile strength | 49.85 MPa |
| Thermal conductivity | 0.09 W/m-K |

**Fig. 3.5** Short banana fiber used as filler in the present work

## 3.2 Experimental details

### 3.2.1 Composite fabrication

**Set 1** Epoxy composites reinforced with short glass fibers for the validation of FEM Modeling

Low temperature curing epoxy resin (LY 556) and corresponding hardener (HY951) are mixed in a ratio of 10:1 by weight as recommended. Short glass fibers were reinforced in the resin to prepare the composites in different proportions according to the requirement. The uniformly mixed dough (epoxy filled with SGF) is then slowly decanted into the glass molds, coated beforehand with wax and a uniform thin film of silicone-releasing agent. The composites were cast in these molds so as to get disc type specimens (diameter 50 mm, thickness 3 mm). Composites of 6 different compositions with different volume fraction are made. The castings were left to cure at room temperature for about 24 hours after which the glass moulds are broken and samples are released. Table 3.4 provides the details of different composition of fabricated composites using glass fiber as filler for the validation of FEM modeling.

A schematic diagram of the fabrication process using hand-layup technique for fiber reinforced epoxy composites is given in figure 3.6. Figure 3.7 and Figure 3.8 shows some of these composite samples prepared through this hand-layup technique.

**Set 2** Epoxy Composites reinforced with short banana fibers for the validation of FEM Modeling

In a similar manner, epoxy composites of 6 more different compositions with different volume fraction were made for short banana fibers.

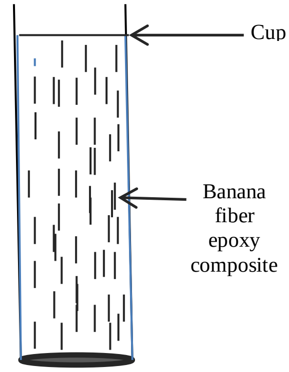




**Fig. 3.6** Fiber reinforced epoxy composite fabrication by hand lay-up process

For each composition, the composites were cast in glass moulds so as to get both disc type specimens with similar dimensions. Table 3.4 also provides the details of different composition of fabricated composites using banana fiber as filler for the validation of FEM modeling.

**Table 3.4** List of fiber-reinforced polymer composites fabricated by hand-lay-up technique for the validation of FEM modelling

| **Sample** | **Composition (Glass fiber as filler material )** | **Composition (Banana fiber as filler material )** |
|---|---|---|
| **1.** | Epoxy + 2.83 vol% Glass fiber | Epoxy + 2.83 vol% Banana fiber |
| **2.** | Epoxy + 5.65 vol% Glass fiber | Epoxy + 5.65 vol% Banana fiber |
| **3.** | Epoxy + 7.54 vol% Glass fiber | Epoxy + 7.54 vol% Banana fiber |
| **4.** | Epoxy + 10.05 vol% Glass fiber | Epoxy + 10.05 vol% Banana fiber |
| **5.** | Epoxy + 12.56 vol% Glass fiber | Epoxy + 12.56 vol% Banana fiber |
| **6.** | Epoxy + 15.7 vol% Glass fiber | Epoxy + 15.7 vol% Banana fiber |

**Set 3** Epoxy Composites reinforced with short glass fibers for the validation of Mathematical Model

Using the same hand lay-up technique, short glass fibers were reinforced in the resin to prepare the composites of 6 different compositions with different volume fraction. The composites were cast on to glass moulds so as to get disc type specimens of dimensions with similar dimensions which are shown in figure 3.7. Table 3.5 provides the details of different composition of fabricated composites using glass fiber as filler for the validation of Mathematical modelling.

**Set 4** Epoxy Composites reinforced with short banana fibers for the validation of Mathematical Model

In a similar manner, epoxy reinforced with short banana fibers composites of 6 more different compositions were made and for each of these compositions, the composites were cast in glass moulds so as to get both disc type specimens with same dimensions which are shown in figure 3.8. Table 3.5 also provides the details of different composition of fabricated composites using banana fiber as filler for the validation of Mathematical modelling.

**Table 3.5** List of fiber-reinforced polymer composites fabricated by hand-lay-up technique for the validation of Mathematical model

| Sample | Composition (Glass fiber as filler material ) | Composition (Banana fiber as filler material ) |
|---|---|---|
| 1. | Epoxy + 2.83 vol% Glass fiber | Epoxy + 2.83 vol% Banana fiber |
| 2. | Epoxy + 5.65 vol% Glass fiber | Epoxy + 5.65 vol% Banana fiber |
| 3. | Epoxy + 7.54 vol% Glass fiber | Epoxy + 7.54 vol% Banana fiber |
| 4. | Epoxy + 10.05 vol% Glass fiber | Epoxy + 10.05 vol% Banana fiber |
| 5. | Epoxy + 12.56 vol% Glass fiber | Epoxy + 12.56 vol% Banana fiber |
| 6. | Epoxy + 15.7 vol% Glass fiber | Epoxy + 15.7 vol% Banana fiber |

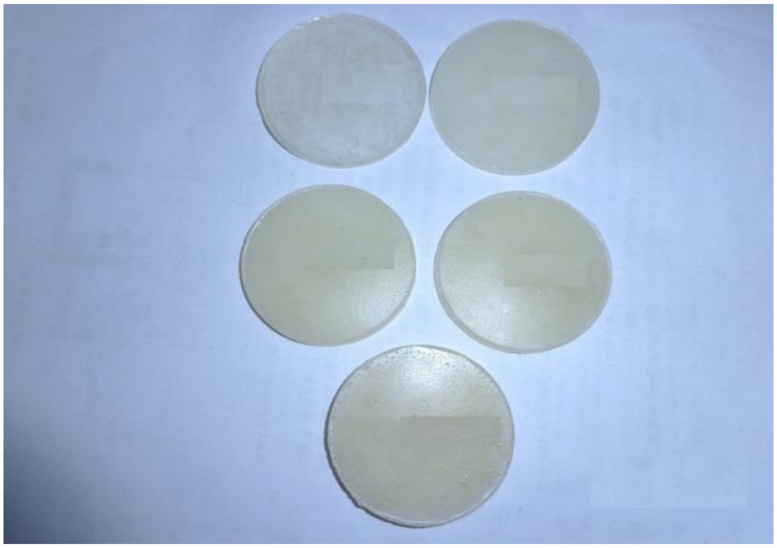


**Fig. 3.7** Short glass fiber reinforced epoxy composites

**Fig. 3.8** Short banana fiber reinforced epoxy composites

## 3.3 Thermal conductivity characterization

### 3.3.1 Experimental determination of thermal conductivity:

**Unitherm Model 2022 Guarded Heat Flow Meter Thermal Conductivity Measurement System from Nortest.**

The thermal conductivity of various materials is measured by the Unitherm Model 2022. These materials include polymers, composites, ceramics, glasses, rubbers, some metals and other materials of low to medium thermal conductivity. A minor sample test material is required to find out the thermal conductivity. Different containers are used to measure thermal conductivity of non-solids materials, such as glues or pastes or fluids. The tests are in accordance with **ASTM E-1530** Standard. A hermetically sealed section is used to make atmosphere free form moisture with dry air purge for testing at temperatures below ambient. The thermal conductivity of polymers is measured through the melt using Superior suppression cells.

### 3.3.2 Operating principle of Unitherm-TM 2022:

Optional chiller circulator is provided for full utilization of the range of the instrument that can provide heat sink temperature to -10°C or for the cryogenic model, to -60°C. The Unitherm Model 2022 is provided with one of three operating range modules. Different thermal resistance area is covered by each module and each of the modules is field replaceable.

A uniform compressive load is given to sample test material between two surfaces which are controlled at a different temperature. Calibrated heat flow transducer is connected to the lower surface of sample test material.

The direction of the heat flow within the sample is from upper surface to the lower surface for the establishment of an axial temperature difference in the stack. When the thermal equilibrium is maintained, the heat flow transducer gives the output which is the temperature gradient through the sample and it is found with the help of reading of the transducer. The thermal conductivity of the sample test material is found using the measured values and the thickness of the sample. Temperature sensors are used to calculate the drop in temperature through the sample test material in the highly conductive metal surface layers on either side of the sample.

**Fig. 3.8** Determination of Thermal Conductivity Using Unitherm™ Model 2022

We know that thermal conductivity of the material gives the amount of energy conducted through a body of unit area and unit thickness in unit time when the difference in temperature between the faces causing heat flow is unit temperature difference. The Fourier’s equation for one-dimensional heat conduction is given as equation 3.1.

$$Q = KA\frac{T_1 - T_2}{x} \tag{3.1}$$

Where,

Q = the heat transfer in W

K = the thermal conductivity of the material in W/m-K

A = the cross sectional area through which heat is transferred in $m^2$

$T_1$-$T_2$ = the temperature difference in K and

X = the thickness of the sample in m.

The thermal resistance of a test sample material can be given as

$$R = \frac{T_1 - T_2}{Q / A} \tag{3.2}$$

Where,

R = the resistance of the sample in $m^2$-K/W.

From Equations 4.1 and 4.2 we can derive that.

$$K = \frac{x}{R} \tag{3.3}$$

In Unitherm model2022, heat flux are measured with the help of heat flow transducer the temperature gradient through the sample test material between the upper plate and lower plate are obtained. Thus the thermal resistance of sample can be calculated between in the upper and lower surfaces. The thermal conductivity of the samples can be calculated using the input value of thickness and taking the known cross sectional area

## 3.4 Numerical analysis: concept of finite element method (FEM) and ANSYS

The finite element method (FEM), or finite element analysis (FEA), is very powerful and simple tool for the analysis of complex physical and engineering problems. In the FEM analysis, the domain of the complex problems or objects is converted into a finite no. of elements or pieces for making it simple analysis. The investigation is concentrated on these elements rather than the whole problem. The complex object has an infinite number of degrees-of-freedom (DOF), while the discretized model has a finite number of DOF. Because of this reason, this method is called as finite element method or finite element analysis. Firstly FEM is used to investigate the stress distribution in complicated aircraft structure. Then it is applied to other field of continuum mechanics, like that Acoustics, heat transfer, fluid mechanics, electromagnetic, biomechanics, aeromechanics. We can say that the FEM analysis can be gainfully used in our daily life problems and also in complex problems of engineering fields. . Powerful computational technique for the solution of differential equations too complicated to be solved satisfactorily by classical analytical methods. The FEM analysis was firstly used in 1956 by Turner. It is most a powerful and simple computational tool for imprecise solutions to a variability of "real-world" engineering problems. FEM analysis can be used for designing the physical phenomenon in various engineering disciplines.

In the FEM analysis, the domain or area of the continuum are converted into a finite number of sub areas i.e. elements which depend on the basis of FEM analysis. Biased residual methods are used for the construction of the orderly approximate solution. In the FEM analysis, the complex problem is reduced to simple analysis by dividing the domains or areas into finite no. of elements and these elements are associated an approximate function to express the unknown field variable. These functions (also called interpolation functions) are defined in terms of the values of the field variables at specific points, referred to as nodes. Nodes are usually located along the element boundaries and they connect adjacent elements.

### 3.4.1 Essential steps in FEM

The steps for the finite element method are as follows.

- Discretization
- Selection of the Displacement Models
- Deriving Element Stiffness Matrices
- Assembly of Overall Equations /Matrices
- Solutions for Unknown Displacements
- Computations for the Strains /Stresses

First, the governing differential equation of the problem is converted into an integral form.

There are two techniques to achieve this:

(i) Variational Technique

(ii) Weighted Residual Technique.

In the variational technique, the calculus of variation is used to obtain the integral form corresponding to the given differential equation. The solution of the problem is obtained by minimizing the integral.

In the second step, Discretization of the solution domain into appropriate computational of the mesh means problem is divided into a number of parts, called as elements.

(1-D) problems, the elements are nothing but line segments having only length and no shape. For problems of higher dimensions, the elements have both the shape and size. For two-dimensional (2D) or axi-symmetric problems, the elements used are triangles, rectangles and quadrilateral having straight or curved boundaries.

When the domain boundary is curved, curved sided elements are good choice. For three-dimensional (3-D) problems, the shapes used are tetrahedron and parallelepiped having straight or curved surfaces. Division of the domain into elements is called a mesh.

In this step, over a typical element, a suitable approximation is chosen for the primary variable of the problem using interpolation functions (also called as shape functions) and the unknown values of the primary variable at some pre-selected points of the element, called as the nodes. Usually polynomials are chosen as the shape functions. For 1-D elements, there are at least 2 nodes placed at the endpoints. Additional nodes are placed in the interior of the element. For 2-D and 3-D elements, the nodes are placed at the vertices (minimum 3 nodes for triangles, minimum 4 nodes for rectangles, quadrilaterals and tetrahedral and minimum 8 nodes for parallelepiped shaped elements).

In the fourth step, the approximation for the primary variable is substituted into the integral form. If the integral form is of variational type, it is minimized to get the algebraic equations for the unknown nodal values of the primary variable. If the integral form is of the weighted residual type, it is set to zero to obtain the algebraic equations.

In this step, the post-processing of the solution is done. That is, first the secondary variables of the problem are calculated from the solution. Then, the nodal values of the primary and secondary variables are used to construct their graphical variation over the domain either in the form of graphs (for 1-D problems) or 2-D/3-D contours as the case may be.

## 3.5 Benefits of the FEM over former numerical methods are as follows:

- In FEM no geometric limitation, it can be applied the body or region with any shape of product.
- Boundary loading and conditions are not restricted (boundary condition and load may be applied to any portion of the body.
- Domain problems consisting of more than one material (composite) can be easily analyzed.
- The method can be used for any irregular-shaped domain and all types of boundary conditions.
- Accuracy of the solution can be improved either by proper refinement of the mesh or by choosing approximation of higher degree polynomials. The algebraic equations can be easily generated and solved on a computer. In fact, a general purpose code can be developed for the analysis of a large class of problems.
- FE structures closely resemble the actual body or region to be analyzed.
- The results and the analysis are easily improved by mesh refinement.
- In the finite element method it is easy to produce detailed visualizations of a complex problem.

## 3.6 A finite element package: ANSYS

For present work, finite element method is used for the study of thermal conductivity of the fiber reinforced polymer composite. A well-known finite element package ANSYS is used to calculate the effective thermal conductivity of fiber reinforced polymer composites. For the ANSYS modelling, short fibers, which are in cylindrical shape, are placed systematically in a cube lattice to simulate the microstructure of the composite lamina used. For different fiber loadings, the three dimensional physical model is prepared for the thermal analysis. Moreover, the effective thermal conductivity of these prepared epoxy composites reinforced with short fibers ranging from 0 to 15.7 vol % is numerically determined using ANSYS.

The steps used in ANSYS for calculating the thermal conductivity are as follows:

1. In the very first step we have to select the preference for the study. There are so many fields are available in ANSYS like thermal, fluid dynamics, structural design etc. As the present study is based on the thermal analysis so preference is given as thermal.

2. In the second step we have to select the preprocessor. In this step element type, description of work and type of node is selected. For present work have selected the thermal solid mass with 8 node brick 70 node is used.

3. In this step the material types and properties are described. For present work materials used are epoxy, glass fiber and banana fiber. The thermal conductivity for all these materials is described in this step.

4. The next step is modeling of the composite lamina. The shape of epoxy resin is taken as square in which the short cylindrical fibers are placed systematically. Three dimensional cylinders in cube lattice array are arranged for the present work. The no. of fibers in the cube depends upon the fiber loading. Finally all the created geometry is overlapped on each other for the meshing.

5. Now in this step meshing of the geometry is done. The type of meshing, size of the meshing etc. are described in this step. The accuracy of the results depends of the meshing. As good as meshing, the accuracy of the results increase.

6. In the next step, solution of the problem is done. For the solution purpose we have to first define the loads on all the faces of composite lamina. For present work, only one dimensional heat transfer is assumed within the composite system so we have to select the input for heat conducting face. Input is given in form of temperature. On the opposite face we have to select the heat transfer coefficient for convection and also the ambient temperature. All the other face is assumed as adiabatic.

7. This is the last step in which results of the analysis are found. The temperature profile for the composite system is found in this step. With the help of temperature profile we can calculate the effective thermal conductivity of composite system.

This is the procedure for calculating thermal conductivity of the composites with the help of ANSYS.

## Chapter Summary

This chapter has provided:

- A description of the finite element method.
- The description of the steps used in ANSYS.
- The details of materials used in the experiments.
- The details of fabrication of the composites by hand-lay-up technique.
- The description of thermal conductivity measurement.

The next chapter presents the results of the numerical analysis, mathematical model and experiments conducted to measure the thermal conductivity of the polymer composites under study.

*******

# Chapter - 4

## RESULTS AND DISCUSSION

### 4.1 Numerical analysis and theory of finite element method

The finite element analysis (FEA) or the finite element method (FEM) is a powerful tool used in numerical methods to arrive at approximate solutions to mathematical problems so that it can simulate the responses of physical systems to various forms of excitation. In the FEM analysis, the complex problems are reduced to simple one by converting the whole domain into a finite number of elements or pieces and for each element an approximate function is associated for the unknown field variables. Now the investigations are concentrated to these elements rather than the whole complex problem. Further, the analysis of thermal conductivity over the composite lamina is done with the help of a well-known FEM package ANSYS. For the ANSYS modelling, short fibers, which are in cylindrical shape, are placed systematically in a cube lattice to simulate the microstructure of the composite lamina used. For different fiber loadings, the three dimensional physical model is prepared for the thermal analysis. Moreover, the effective thermal conductivity of these prepared epoxy composites reinforced with short fibers ranging from 0 to 15.7 vol % is numerically determined using ANSYS.

### 4.2 Description of the problem

Fig. 4.1 shows the direction of heat flow within the composite lamina and the boundary conditions taken for the study of this heat transfer problem for the composite system reinforced by short fibers. The input of this heat transfer problem is in the form of temperature which is given at the nodules along the surface ABEF. The temperature on the surface ABEF is given as 100$^{o}$C. There is a convective heat transfer from the composite lamina to the ambient air and the heat transfer coefficient for convection is supposed to be 2.5 W/m$^{2}$-K at an ambient temperature of 27°C. All the other faces parallel to direction of the flow of heat are supposed adiabatic. The unknown temperatures at the inner nodes and on the other boundaries are obtained with the help of ANSYS.

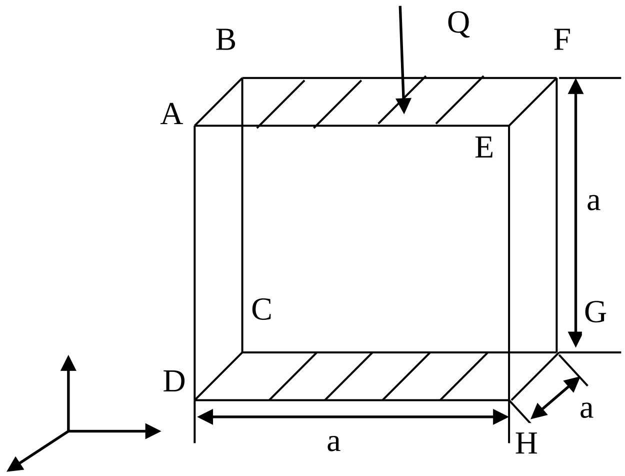
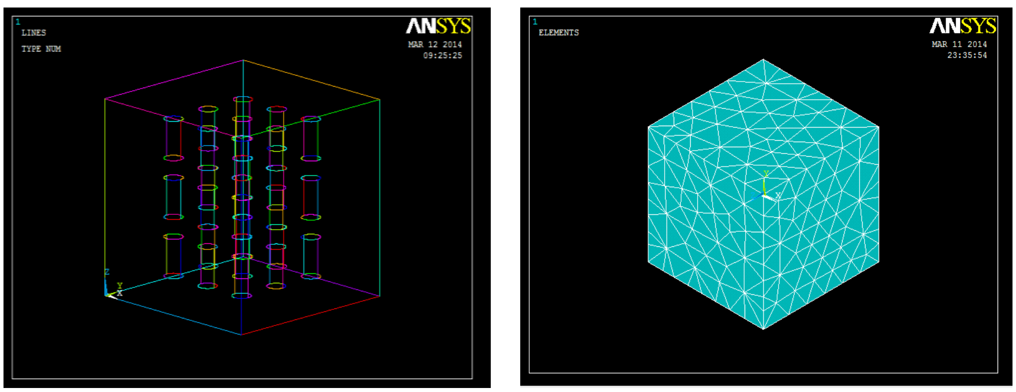



**Fig. 4.1** Boundary condition




(a) (b)

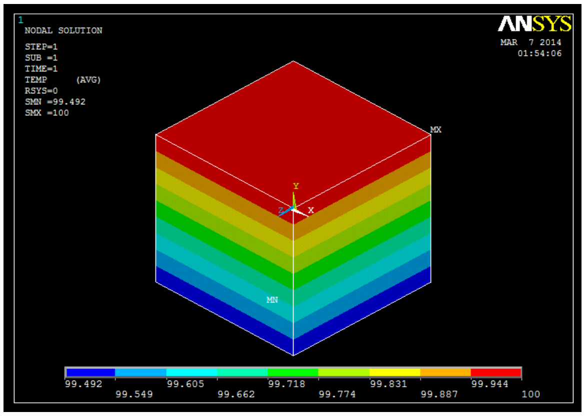
**Fig. 4.2** Three dimensional view of short fiber in cube model (a) fiber arrangement within matrix body, (b) Meshing of such model

## 4.3 Effective thermal conductivity of the composites

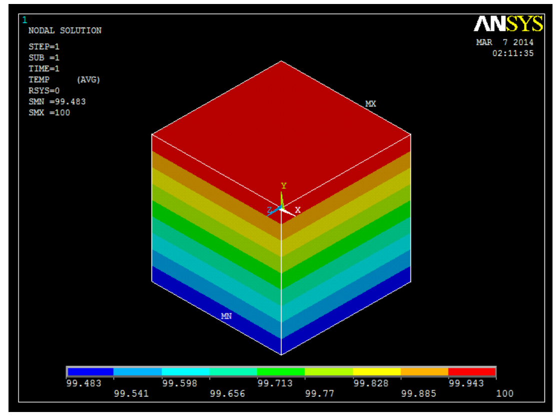
Fig. 4.2 shows the three dimensional view of short fiber in cube model. A typical arrangement of short fiber within the matrix body is shown in Fig. 4.2(a) where fibers are uniformly distributed within the resin and heat is transferred from top to bottom along the axial direction of the fiber. Fig. 4.2(b) shows the meshed view of such fiber in cube model where size of the meshing element purely depends upon the dimension of short fiber.

By applying the various boundary conditions, the temperature profiles can be obtained which are presented in Fig. 4.3 and Fig. 4.4.

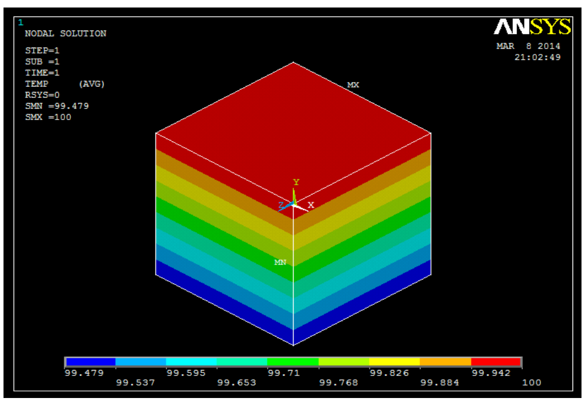
Fig 4.3(a-f) shows the temperature profiles for glass fiber reinforced epoxy composites with fiber volume fraction of 2.83, 5.65, 7.54, 10.05, 12.56 and15.7 vol% respectively.



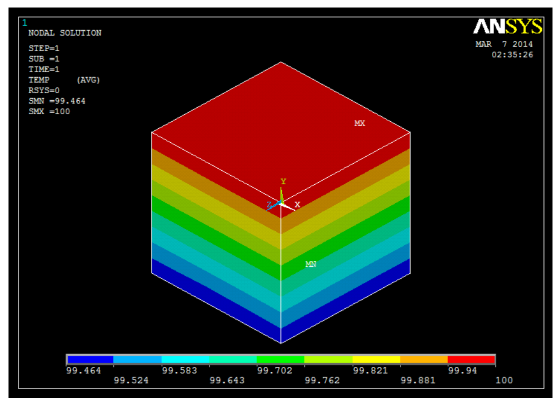

(a)



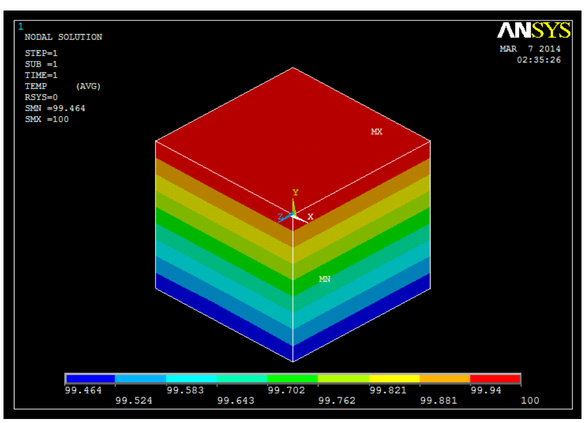

(b)



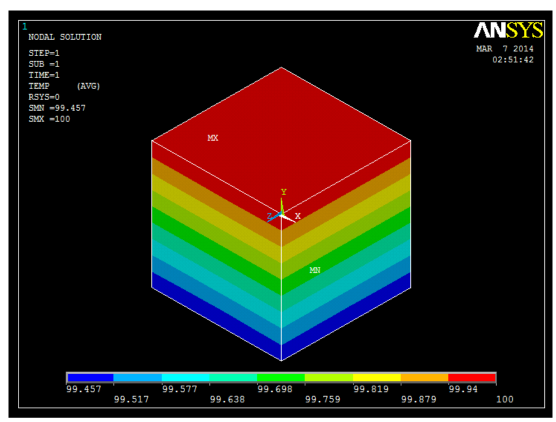

(c)




(d)



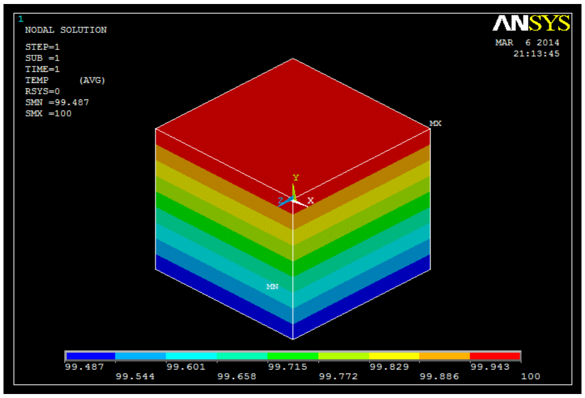

(e)



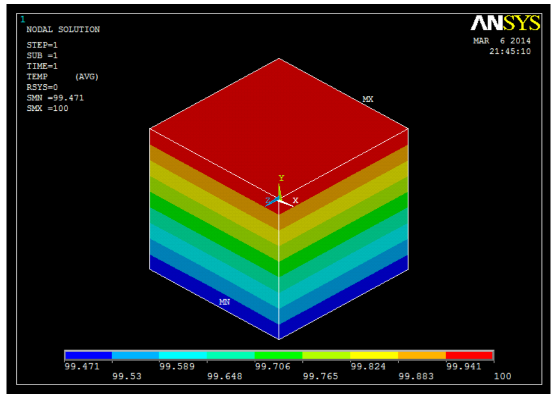

(f)

**Fig. 4.3** Temperature profile of composites with glass fiber loading of (a) 2.83 vol% (b) 5.65 vol% (c) 7.54 vol% (d) 10.05 vol% (e) 12.56 vol% (f) 15.7 vol%

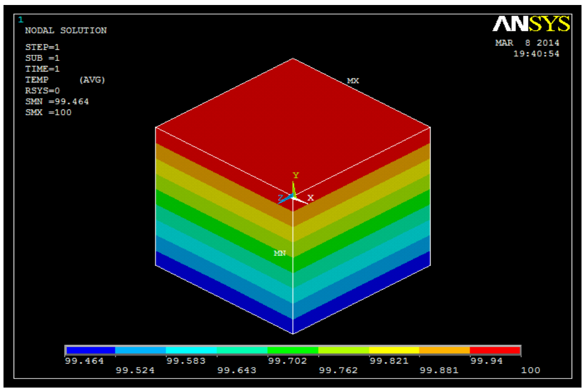
The corresponding temperature profiles for banana fiber reinforced epoxy composites are shown in Fig. 4.4(a-f).



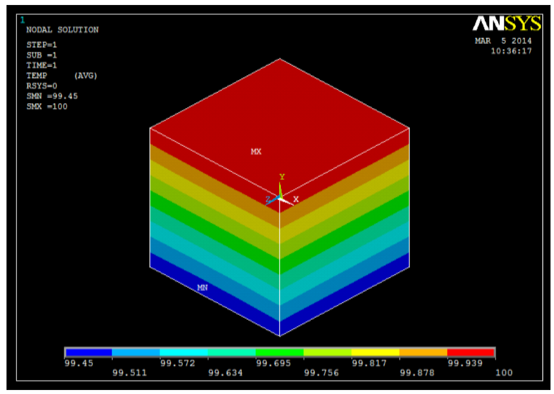

(a)



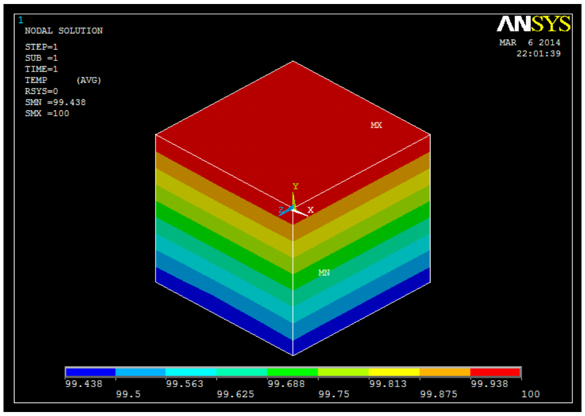

(b)



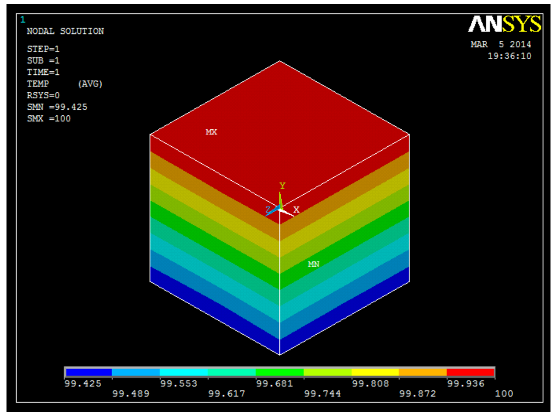

(c)




(d)




(e)




(f)

**Fig. 4.4** Temperature profile of composites with banana fiber loading of (a) 2.83 vol% (b) 5.65 vol% (c) 7.54 vol% (d) 10.05 vol% (e) 12.56 vol% (f) 15.7 vol%

With the help of various temperature profiles, $k_{eff}$ values for different sets of epoxy-fiber composites are calculated.

The $k_{eff}$ values for different methods along with the experimental values for glass fiber reinforced epoxy composites are shown in table 4.1. The similar values for banana fiber reinforced epoxy composites are shown in table 4.2.

**Table 4.1** The $k_{eff}$ values for composites obtained from different methods for glass fiber reinforced epoxy composites

| Sample | Fiber loading (vol%) | Effective thermal conductivity of the composite (W/mK) | | | | | |
|---|---|---|---|---|---|---|---|
| | | ROM | Maxewell model | Lewis-Nilsen model | Proposed model | Experi. values | FEM |
| 1 | 2.83 | 0.353 | 0.356 | 0.357 | 0.357 | 0.360 | 0.357 |
| 2 | 5.65 | 0.343 | 0.350 | 0.345 | 0.352 | 0.356 | 0.350 |
| 3 | 7.54 | 0.337 | 0.346 | 0.339 | 0.349 | 0.352 | 0.347 |
| 4 | 10.05 | 0.328 | 0.340 | 0.329 | 0.343 | 0.346 | 0.342 |
| 5 | 12.56 | 0.322 | 0.336 | 0.323 | 0.339 | 0.341 | 0.338 |
| 6 | 15.7 | 0.313 | 0.329 | 0.313 | 0.334 | 0.337 | 0.333 |

**Table 4.2** The $k_{eff}$ values for composites obtained from different methods for banana fiber reinforced epoxy composites

| Sample | Fiber loading (vol%) | Effective thermal conductivity of the composite (W/mK) | | | | | |
|---|---|---|---|---|---|---|---|
| | | ROM | Maxewell model | Lewis-Nilsen model | Proposed model | Experi. values | FEM |
| 1 | 2.83 | 0.334 | 0.353 | 0.354 | 0.355 | 0.359 | 0.353 |
| 2 | 5.65 | 0.309 | 0.343 | 0.345 | 0.347 | 0.352 | 0.342 |
| 3 | 7.54 | 0.295 | 0.336 | 0.339 | 0.342 | 0.348 | 0.338 |
| 4 | 10.05 | 0.275 | 0.326 | 0.329 | 0.334 | 0.342 | 0.329 |
| 5 | 12.56 | 0.263 | 0.319 | 0.323 | 0.328 | 0.336 | 0.322 |
| 6 | 15.7 | 0.246 | 0.308 | 0.313 | 0.319 | 0.329 | 0.315 |

The comparison of effective thermal conductivity of glass fiber reinforced epoxy composites obtained from various established model like Rule of Mixture, Maxwell's model and Bruggeman's model together with proposed model, FEM analysis and experimental values are shown in Fig. 4.5.

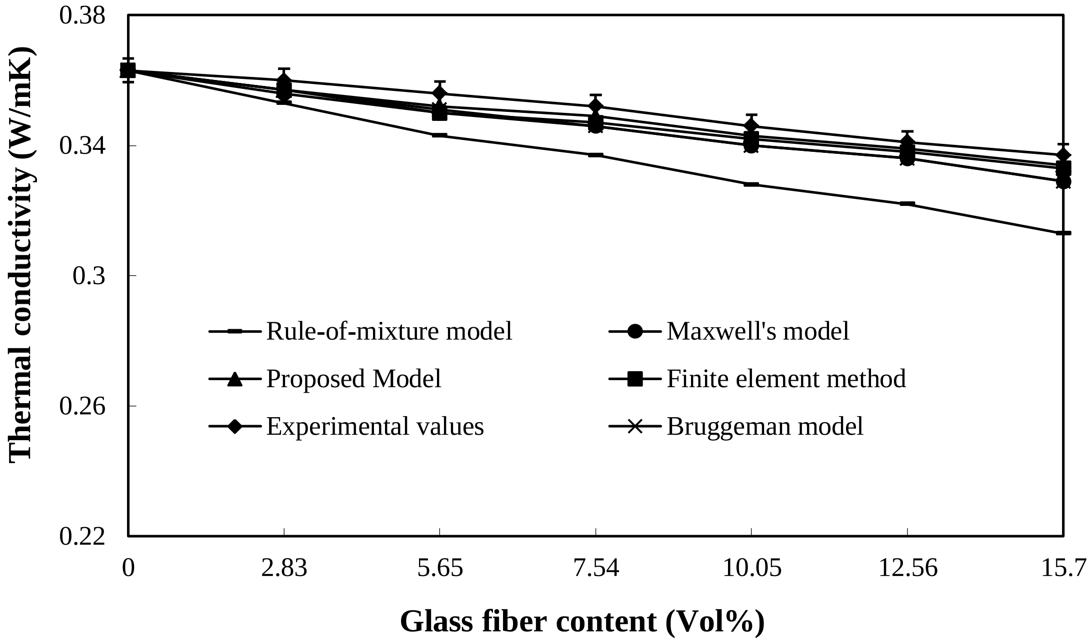



**Fig. 4.5** Effective thermal conductivity of short glass fiber/epoxy composites: Rule-of mixure, Maxwell's model, Bruggeman model, Proposed model, FEM and Experimental values

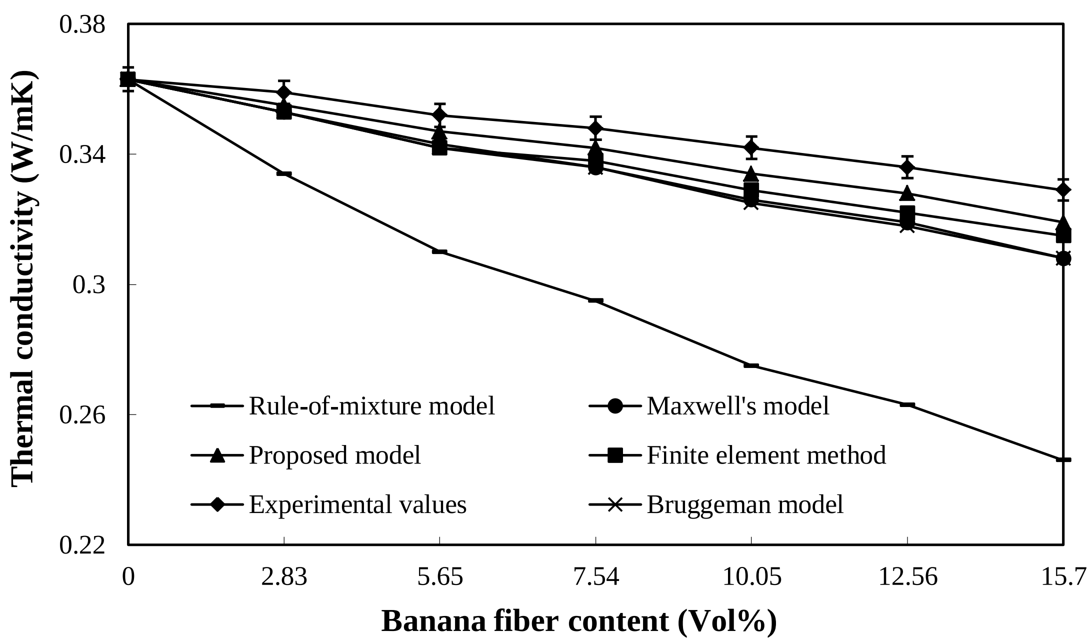



**Fig. 4.6** Effective thermal conductivity of short banana fiber/epoxy composites: Rule-of mixure, Maxwell's model, Bruggeman model, Proposed model, FEM and Experimental values

The similar comparison for banana fiber reinforced epoxy composites are shown in Fig. 4.6.

From both the figures, it is observed that as the fiber loading in the epoxy resin increases, the values of $k_{eff}$ decreases which is obvious because both the fibers possesses low value of intrinsic thermal conductivity as compared to epoxy resin. The trend is followed by all the analytical models, numerical model and measured values.

Further it is noticed that the values obtained from Maxwell's model, Bruggeman's model, proposed model and FEM analysis fit well with the experimental data whereas rule of mixture model is far from satisfaction.

The percentage error associated with each of the method used in present investigation for glass fiber-epoxy composites are presented in table 4.3.

The similar percentage error associated with each of the method used in present investigation for banana fiber-epoxy composites are presented in table 4.4.

**Table 4.3** Percentage errors associated with respect to experimental value for glass fiber/epoxy composites

| Sample | Fiber loading (vol%) | Percentage errors with respect to experimental value | | | | |
|---|---|---|---|---|---|---|
| | | Rule of mixture | Maxewell model | Bruggeman model | Proposed model | FEM |
| 1 | 2.83 | 1.983 | 1.123 | 0.841 | 0.843 | 0.840 |
| 2 | 5.65 | 3.790 | 1.714 | 1.424 | 1.424 | 1.714 |
| 3 | 7.54 | 4.451 | 1.734 | 1.149 | 1.734 | 1.440 |
| 4 | 10.05 | 5.487 | 1.764 | 1.169 | 1.765 | 1.169 |
| 5 | 12.56 | 5.901 | 1.488 | 1.186 | 1.488 | 0.887 |
| 6 | 15.7 | 7.667 | 2.431 | 1.813 | 2.431 | 1.201 |

From the tables it is observed that the errors associated with respect to the experimental values for glass fiber reinforced epoxy composite for proposed model, FEM values, Maxwell's model and Bruggeman's model lie in range of 0.8-2% and for rule-of mixture model it gets widen up to 2-8%.

**Table 4.4** Percentage errors associated with respect to experimental value for banana fiber/epoxy composites

| Sample | Fiber loading (vol%) | Percentage errors with respect to experimental value | | | | |
|---|---|---|---|---|---|---|
| | | Rule of mixture | Maxwell's model | Bruggeman model | Proposed model | FEM |
| 1 | 2.83 | 7.485 | 1.608 | 1.699 | 1.127 | 1.169 |
| 2 | 5.65 | 13.548 | 2.624 | 2.924 | 1.441 | 2.924 |
| 3 | 7.54 | 17.966 | 3.571 | 3.571 | 1.754 | 2.958 |
| 4 | 10.05 | 24.363 | 4.908 | 5.231 | 2.395 | 3.951 |
| 5 | 12.56 | 27.756 | 5.329 | 5.660 | 2.439 | 4.347 |
| 6 | 15.7 | 33.739 | 6.818 | 6.818 | 3.135 | 4.444 |

Again for banana fiber reinforced epoxy composites the errors associated with respect to measured values for proposed model and FEM values lie in the range of 1-4%, for Maxwell's model and Bruggeman's model lie in range of 1.6-7% and for rule-of mixture it is in range of 7-34%. It is observed that the values obtained from the proposed model and FEM simulation are showing least percentage variation with measured values when both sets of composites are considered for the complete range of fiber loading, whereas Maxwell's and Brugmann's model show more variation with respect to measured value for banana fiber epoxy composites as compared to glass fiber-epoxy composites. It is seen that rule-of-mixture model underestimates the measured values completely for both sets of composites. It can be observed that for predicting the effective thermal conductivity of composites for a wide range of fiber concentration, proposed model and FEM model are giving the most suitable results.

Further it can be seen that banana fiber reinforced epoxy composites shows much lower $k_{eff}$ values than that of glass fiber reinforced epoxy composites. The comparison of the $k_{eff}$ values of both banana fiber and glass fiber reinforced epoxy composites for proposed model are given in Fig. 4.7. The comparison of the $k_{eff}$ values of both banana fiber and glass fiber reinforced epoxy composites for FEM model are given in Fig. 4.8.

The similar comparison of the $k_{eff}$ values of both banana fiber and glass fiber reinforced epoxy composites for experiment are given in Fig. 4.9.

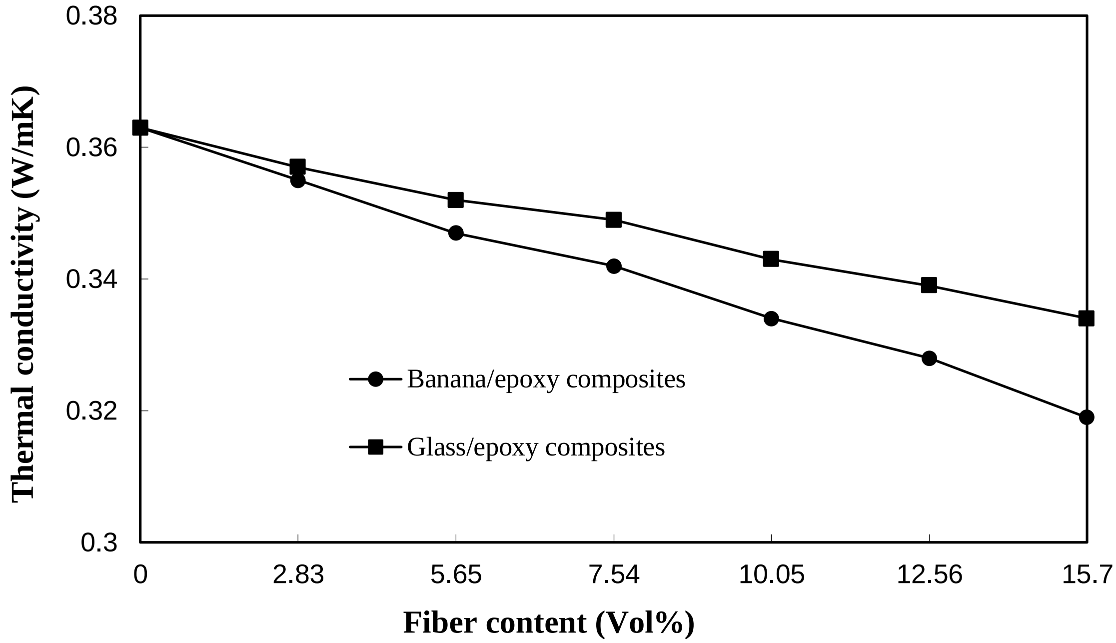



**Fig. 4.7** Comparison of the $k_{eff}$ values for the proposed model for both the filler

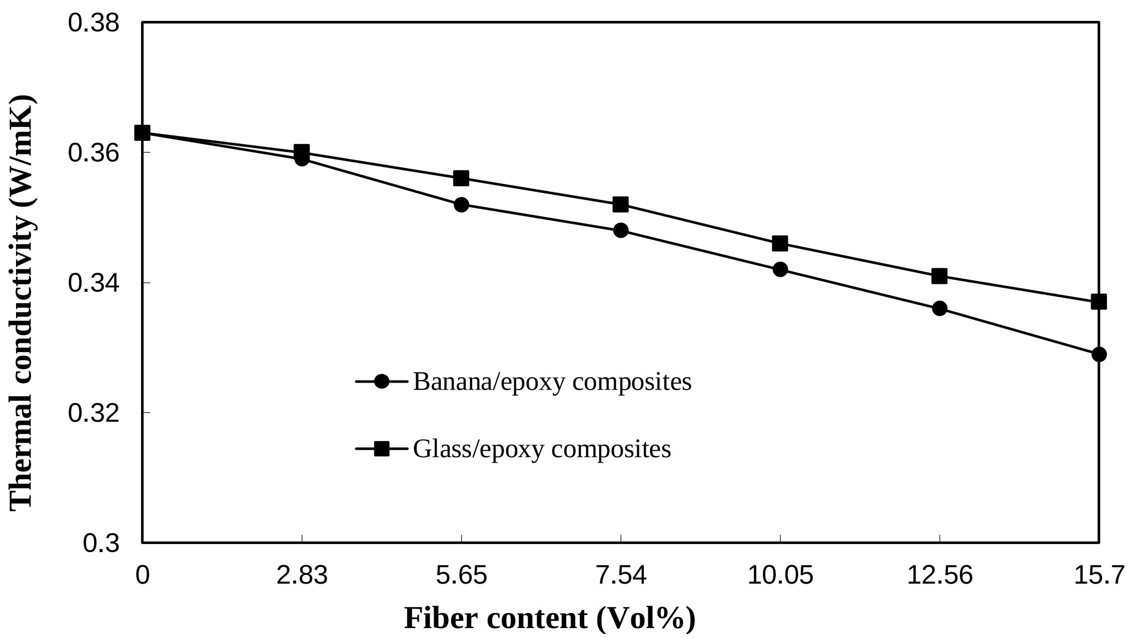



**Fig. 4.8** Comparison of the $k_{eff}$ values for the FEM model for both the filler

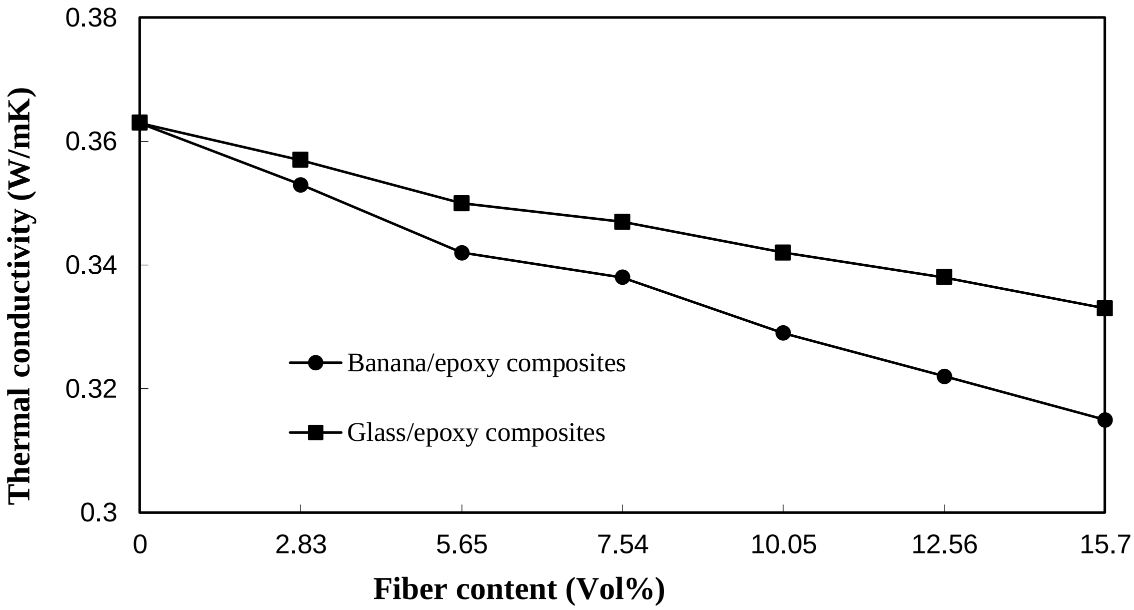



**Fig. 4.9** Comparison of the $k_{eff}$ values for the experiment for both the filler

It can be seen from the comparison graph that reduction in the $k_{eff}$ values for banana fiber reinforced polymer composites is more than the glass fiber reinforced polymer composites which is obvious because banana fiber has lower thermal conductivity than glass fiber. Banana fibers have also properties like non-corrosive, biodegradable, low cost, recyclable etc. So it can be said that a natural fiber i.e. banana fiber can replace a well-known synthetic fiber i.e. glass fiber for insulation purpose used as reinforcement in composite materials.

**Chapter summery**

This chapter has presented the results of the numerical analysis and mathematical model and experiments conducted to evaluate the thermal insulation of the polymer composites under study. The measured values of the effective thermal conductivity are obtained for different volume fractions of fibers. Incorporation of fiber results in reduction of thermal conductivity of epoxy resin and thereby improves its thermal insulation capability. A reduction of 8 % in $k_{eff}$ is obtained for the composites with addition of 15.7 vol % of glass fiber whereas for banana fiber it goes down to 12 % for similar fiber loading. The next chapter presents the conclusions based on the research presented in this thesis along with recommendations for future work.

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Chapter - 5

# CONCLUSİON AND SCOPE OF THE FUTURE WROK

## 5.1 Conclusion

Based on the numerical, analytical and experimental investigation on the thermal conductivity of fibers (glass fiber and banana fiber) reinforced composites, it can be concluded that:

1. Different sets of epoxy/ glass fiber and epoxy/banana fiber composites can be successfully fabricated by simple hand lay-up technique for varied volume concentration.

2. The values obtained from the proposed mathematical model are in close approximation with the measured values for all the fabricated composites over the entire range of fiber content.

3. The results obtained from the proposed mathematical model are also in closer approximation with the values obtained by FEM simulation using ANSYS.

4. It is seen that the Finite element method (FEM) can be gainfully employed for determination of effective thermal conductivity of fiber reinforced polymer composites with different volume concentration of fiber.

5. The study shows that the $k_{eff}$ reduces quite significantly as the fiber loading in the composite increases. A reduction of about 8 % in the value of the $k_{eff}$ is recorded with addition of 15.7 vol % of glass fiber in epoxy resin whereas 12 % decrease is noticed when filler is banana fiber.

6. Also is can be concluded that banana fiber reinforced epoxy composites shows much lower $k_{eff}$ values than that of glass fiber reinforced epoxy composites. Banana fibers have also properties like non-corrosive, biodegradable, low cost, recyclable etc. So it can be said that a natural fiber i.e. banana fiber can replace a well-known synthetic fiber i.e. glass fiber for insulation purpose used as reinforcement in composite materials.

7. With light weight and reduced heat conductivity, these fibers reinforced polymer composites finds their potential applications in insulation boards, food containers, thermo flasks, building material etc.

## 5.2 Scope for future work

This work leaves a wide scope for future investigators to explore many other aspects of thermal behaviour of fiber reinforced polymer composites. Some recommendations for future research include:

- Study on effect of filler orientation and size on thermal properties of the composites.
- Investigation of new fillers and polymers for development of materials having low thermal conductivity and low electrical conductivity.
- Possible use of other polymeric resins and natural fibers in the development of new hybrid composites.
- Study on the response of these composites to other wear modes such as abrasion and slurry erosion.
- Study on the effect of filler shape and size on thermal properties of the composites.

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**Appendix – A1**

## List of Publications from the Present Research Work

**International Journal**

1. Johan Banjare, **Yagya Kumar Sahu**, Alok Agrawal and Alok Satapathy. "Physical and thermal characterization of red mud reinforced epoxy composites: An experimental investigation" ***Procedia Materials Science (2014)***. (Accepted)

2. **Yagya Kumar Sahu,** Johan Banjare, Alok Agrawal and Alok Satapathy."An analytical, numerical and experimental investigation on heat conductivity of short fiber reinforced polymer composites". ***Journal of Polymer Research (2014)***. (communicated)

**International Conferences**

1. **Yagya Kumar Sahu**, Johan Banjare, Alok Agrawal and Alok Satapathy. "Establishment of an analytical model to predict effective thermal conductivity of fiber reinforced polymer composites". ***International Conference on Advancements in Polymeric Materials-2014, CIPET Bhubaneswar.***

2. Johan Banjare, **Yagya Kumar Sahu**, Alok Agrawal and Alok Satapathy. "Development of Mathematical Model to Evaluate Effective Thermal Conductivity of Particulate Filled Polymer Composites". ***International conference Emerging Materials and Processes- 2014, CSIR-IMMT Bhubaneswar.***

3. AlokAgrawal, **Yagya Kumar Sahu**, Johan Banjare and Alok Satapathy."Epoxy Composites Filled with Micro-sized $Al_2O_3$ Particles for Microelectronic Applications". ***International Conference on Functional Materials-2014, IIT Kharagpur.***